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SEASONAL FORECASTING OF RAINFALL AND STREAMFLOW FOR THE ELECTRICITY UTILITY IN SOUTH AFRICA

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RESUMO

A África do Sul é um país onde as reservas minerais existem em abundância na natureza, o que propiciou um rápido desenvolvimento da mineração e indústria na região central do país, levando a uma grande demanda por eletricidade, que na sua maioria (85%) é gerada por termoelétricas. A distribuição da precipitação no planalto sul-africano (outubro – abril), apresenta totais anuais entre 600 – 800 mm, fazendo com que a Companhia Geradora de Energia e outras atividades industriais, bem como o importante setor agrícola nessa região, fique vulnerável aos episódios de secas. Pelas razões acima descritas, a partir do início dos anos noventa realizou-se estudos intensivos sobre os mecanismos e a previsão de secas. Esses esforços concentrados resultaram numa previsão sazonal (3 + 3 meses) com resultados aceitáveis. Esta previsão é baseada em saídas de uma variedade de modelos estatísticos e modelos dinâmicos de circulação global, sendo emitida mensalmente pelo Serviço Meteorológico Sul-Africano sob a forma de previsões agrupadas por três intervalos de probabilidades (*categorical*) para diferentes regiões do país. Realizou-se também uma pesquisa para se utilizar um esquema multi-ordenado (*multi-tiered*), combinando saídas de modelos estatísticos e modelos globais “*downscaled*” para se prever diretamente a vazão. Embora ainda num estágio inicial, o método demonstrou uma destreza em níveis aceitáveis para algumas regiões do planalto sul-africano. Ainda na seqüência, dois modelos hidrológicos determinísticos foram adaptados para se utilizar como insumo a previsão de precipitação categorizada para se prever vazões sazonais. Os estudos exploratórios realizados produziram resultados bastante encorajadores. Os possíveis benefícios do uso deste tipo de metodologia e algumas sugestões de aplicações pelo setor elétrico brasileiro serão aqui destacados.

1. INTRODUCTION

South Africa is blessed with an abundance of mineral resources, which has led to the development of mining and industry in the central region of the country. Accompanying the industrial development are a variety of environmental impacts due to the development of the required infrastructure for the industries, such as road and rail transport, opening of mines and quarries to supply raw materials, followed by waste disposal problems affecting air, water and soil, and finally the population growth around major industrial centers. It is therefore of vital importance that such “growth centers” are well planned and continuously monitored, which was well controlled by the government from the 1960s until the mid-80s (Von Gogh and Held, 1982).

However, the vast majority of mineral resources in South Africa, such as precious metals, a wide variety of other mineral deposits and easily accessible coal fields, are concentrated in the central part of the plateau, resulting in a massive accumulation of mining activities and the subsequent development of heavy industries, like metallurgical smelters, gold refineries, petrochemical plants (including the world’s largest coal-to-oil processing complex) and electricity generating plants. All these activities require vast amounts of water for their various processes, but the availability of water in this region is not only subject to a very pronounced seasonal variation due to the different rainfall regimes in South Africa, but it is also critically dependent on the large-scale hemispheric circulation which impacts on the drought cycle (Held, 1994).

Figure 1. The major industrialized region of Mpumalanga and Gauteng (small inserted rectangle) on the South African plateau (topographical map of South Africa extracted from Encarta World Atlas, 1998).

Eskom, the South African electricity utility, is a major user of water resources (the annual consumption is approximately 228 759 Ml; Eskom, 2001) due to the fact that about 85% of its total electricity production is being generated by large thermal power stations, which are all, but one, located in a 250x200 km area (small rectangle in Figure 1). The highveld is primarily a rich agricultural region, for which a reliable water supply is equally important. It is therefore not surprising, that the Department of Water Affairs and Forestry (DWA&F) and Eskom embarked on a strictly controlled water supply/ utilization scheme.

2. DROUGHT CYCLES RISKS IN SOUTH AFRICA AND THE NEED FOR STRICT PLANNING OF WATER RESOURCES

Eskom is the seventh largest electricity utility in the world, both with respect to installed capacity (MW) and sales of electricity (GWh). It operates 24 power stations, with a total installed capacity of 41,9 GW (Eskom, 2001). The vast majority are coal-fired (89%) and located within the high-density industrial area shown in Figure 1 (only the dry-cooled Matimba Power Station is some 350 km north of Johannesburg). The remainder comprises hydroelectric (5%), nuclear power (5%) and gas turbines (1%). The major power stations are listed in Table 1 with details of their generating characteristics. Eskom produces more than 50% of all electricity generated on the African continent and supplies 31% of its total production to industry, most of which is located in the Gauteng, Mpumalanga and North-West provinces, 18% to the mining sector and exports about 3% to neighboring countries (Eskom, 2001).

The average annual rainfall within the relevant catchment areas on the highveld varies from 600-800 mm per year over the central part of the highveld to about 1000 mm per year over the eastern part of the plateau with the mountainous escarpment region (Figure 2). About 90% of it falls during the rainy period from October to April (SAWB, 1986), making water management basically a problem of planning the storage in the wet season and release in the dry period. Therefore, well-designed and managed storage dams are essential for the continuous supply of cooling water. Not only did Eskom and DWA&F invest heavily in a sophisticated pumping scheme, allowing the transfer of water from reservoirs situated in catchments, that received good rainfalls, to those dams which might not be able to supply sufficient water to their designated plants, but it also embarked on an ambitious research program into direct and indirect cooling plants. Ultimately, Eskom installed 17 dry-cooling units in four power stations between 1971 and 1998, generating 10,5 GW (30% of all thermal stations), demonstrating its concern for water conservation.

Table 1. Major Eskom power stations in South Africa (after Eskom, 2001).

Power Station	Fuel	Units No x MW	Cooling	Total Capacity MW *		Power Station	Fuel	Units No x MW	Total Capacity MW
Arnot	C	6 x 350	W	2100		Acacia	G	3 x 57	171
Camden	C	8 x 200	W	(1600)		Port Rex	G	3 x 57	171
Duvha	C	6 x 600	W	3600					
Grootvlei	C	4 x 200 2 x 200	W iD	(1200)					
Hendrina	C	10 x 200	W	2000		Gariep	H	4 x 90	360
Kendal	C	6 x 686	iD	4116		Vanderkloof	H	2 x 120	240
Komati	C	5 x 100 4 x 125	W W	(1000)					
Kriel	C	6 x 500	W	3000		Drakensberg	HP	4 x 250	1000
Lethabo	C	6 x 618	W	3708		Palmiet	HP	2 x 200	400
Majuba	C	3 x 657 3 x 711	dD W	4104					
Matimba	C	6 x 665	dD	3990		Koeberg	N	2 x 956	1930
Matla	C	6 x 600	W	3600					
Tutuka	C	6 x 609	W	3654					
TOTAL				**37 672**					**4 272**

Key:
Fuel - C = coal; G = gas; H = hydro; HP = hydro peaking; N = nuclear
Cooling - W = wet; water through cooling towers
- iD = indirect air cooling through cooling towers
- dD = direct air cooling via radiators
- The gas and nuclear power stations are at the coast, using sea water

***** This reflects installed capacity; the net capacity is slightly less, depending on the age of the units, quality of fuel and efficiency as a function of ambient conditions (iD & dD). ( ) indicates that the power station is in " cold storage" (mothballed).

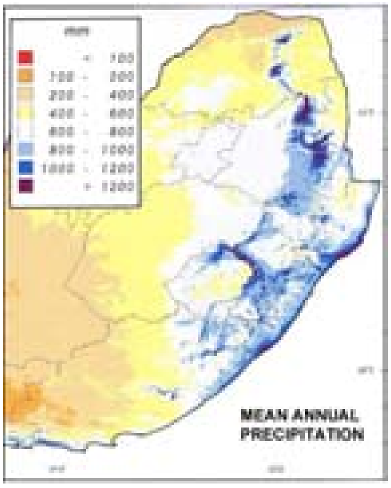

Figure 2. Mean annual precipitation over eastern South Africa (after Schulze, 1997a).

Water resources in South Africa are strictly controlled by the DWA&F using the output of Water Resources Management Models, generally based on stochastic hydrological models, such as the WRSM90, which is the original Pitman Model (Pitman, 1973), which do not allow input of *expected rainfall* based on atmospheric circulation. The monthly stream flow time series are then processed through System Analysis Models, which consider the storage facilities, as well as water requirements of each sector (agriculture, drinking water and industrial needs) and by using monthly catchment rainfall time series (Held, 1999, Appendix 2) allocated water quotas are calculated. Conservative decisions for water allocations are made at the end of the rainy season and hardly ever adjusted (relaxed) if good rainfalls occurred over the catchments. Since a reliable water supply is critical to the operational business of Eskom, it is vitally important to regularly perform a risk analysis on drought cycles.

This paper will put the problem into perspective, from the early attempts in 1993/94, using a simple statistical climatological model to predict seasonal rainfall, to downscaling Global Circulation Models (GCMs) for regional rainfall and ultimately stream flow predictions. Hydrological models were also adapted to run with seasonal rainfall estimates as input after initialization. Ultimately, the reliable prediction of drought cycles on the South African plateau will be endeavored through this research project.

3. THE DEVELOPMENT OF SEASONAL RAINFALL FORECAST IN SOUTH AFRICA

As early as 1993, Eskom Management appreciated the need for long-term, strategic research projects to anticipate the possible impacts of global climate change on its business an the one hand, and on the other hand to investigate the reliability and possible application of seasonal rainfall forecasting for relatively short-term planning of its water resources, preferably at the beginning of the dry season (austral winter months), and other operational activities. These considerations were based on the fact, that the availability of water is not only subject to a very pronounced seasonal variation due to the different rainfall regimes in South Africa (Schulze, 1965), but it is also critically dependent on the large scale hemispheric circulation, including El Niño (dry) and La Niña (wet) events, which all impact on the drought cycle. The periodicity of the drought cycle is most commonly quoted as 10 years, but is subject to large variations. In addition, wet periods can be interrupted by brief spells of dry seasons. Rainfall predictions are based on models using different coupling mechanisms of circulation, temperature distribution and rainfall patterns and can therefore yield quite different answers.

The main objective of the project *Risk Analysis of Drought Cycles* was to perform a realistic assessment of the possibility of a drought or wet season in the near future, utilizing readily available model outputs. For this purpose, the Climatology Research Group (CRG) of the University of the Witwatersrand was contracted during 1994 to conduct a comprehensive literature survey and to do a preliminary assessment (Mason *et al.,* 1994). It was concluded, that the potential for seasonal forecast skill is higher within the tropics than the extratropics, due to the direct coupling between the tropical ocean and atmosphere. The potential for seasonal forecast skill over southern Africa may be largely determined by the lower boundary forcing associated with sea-surface temperature variability in the tropical Pacific Ocean and in the oceans surrounding the subcontinent. Further, the link extending to the extratropics through ENSO- (El-Niño-Southern-Oscillation) related teleconnections may hold potential for seasonal forecast skill (Held, 1994). During 1995, the accuracy and confidence levels of the “Seasonal Rainfall Outlooks” issued by the CRG had been identified and improvements to forecast skills implemented (Mason, 1995). Since other academic groups also ventured into this field, a loose alliance, the South African Long-Lead Forecast Forum (SALFF), was formed by three Universities and the South African Weather Bureau (SAWB) in 1994 (Mason *et al.,* 1994). Eskom actively promoted their interaction by providing two annual platforms for discussions and research planning since 1995, one after the rain season (April/May) to evaluate the performance of the various forecasts, followed by the second Workshop before the beginning of the next rain season (August/September) to give each group a chance to present its outlooks for the forthcoming season. Since each group used different approaches (statistical models with a mixture of predictor variables) to derive their seasonal outlooks, which initially were not much longer than one month, the South African media used small discrepancies in the predictions to play out the groups against each other, which brought the credibility of seasonal forecasting into disrepute with the general public.

As the seasonal forecasting models were improved in their design, yielding useful forecast skill for a reasonable part of South Africa throughout the year, in 1996 the CRG managed for the first time to produce six-months forecasts, which had been cross-validated on an independent 15-year data set (Mason, 1996). At the same time, the need for linking seasonal rainfall predictions with hydrological rainfall-runoff models was realized, and therefore, a feasibility study for a small catchment (Bivane, 952km^2) in northern KwaZulu-Natal (Figure 3) was initiated. The task to develop and assess a methodology to translate categorical medium- to long-range rainfall forecast information into representative daily rainfall sets, for input to the deterministic *ACRU* agrohydrological modeling system (Schulze *et al.*, 1996), in order to facilitate water resources forecasts, was contracted to the University of Natal (Lecler and Schulze, 1997). Although the preliminary results were encouraging, as shown in Figure 4 (correlation coefficient of r = 0.85 and index of agreement d = 0.89 between stream flows simulated with rainfall data that were recorded for a particular season and those using seasonal rainfall outlooks for the same season; Lecler and Schulze, 1997), the fact, that the model predicts stream flow on a daily basis, requiring very detailed catchment information and was found to be extremely sensitive to the rainfall input, discouraged the application for a larger catchment.

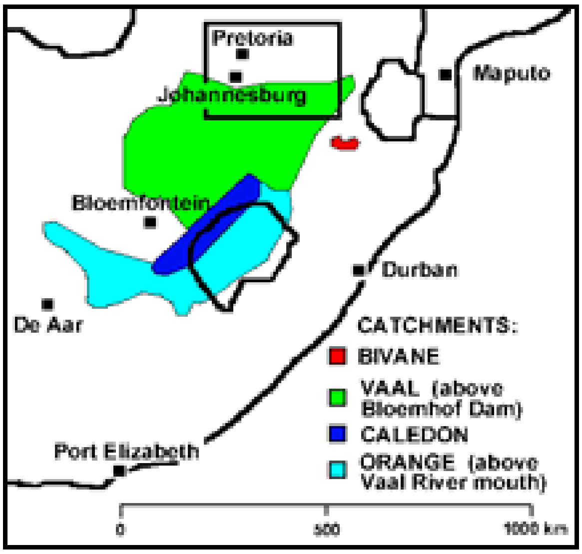

Figure 3. Approximate outlines of the four catchments used for stream flow modeling. The inserted rectangle demarcates the industrial area on the South African plateau with 12 of the 13 thermal power stations. The two hydroelectric plants (H in Table 1) are on the Orange River in the western half of the catchment.

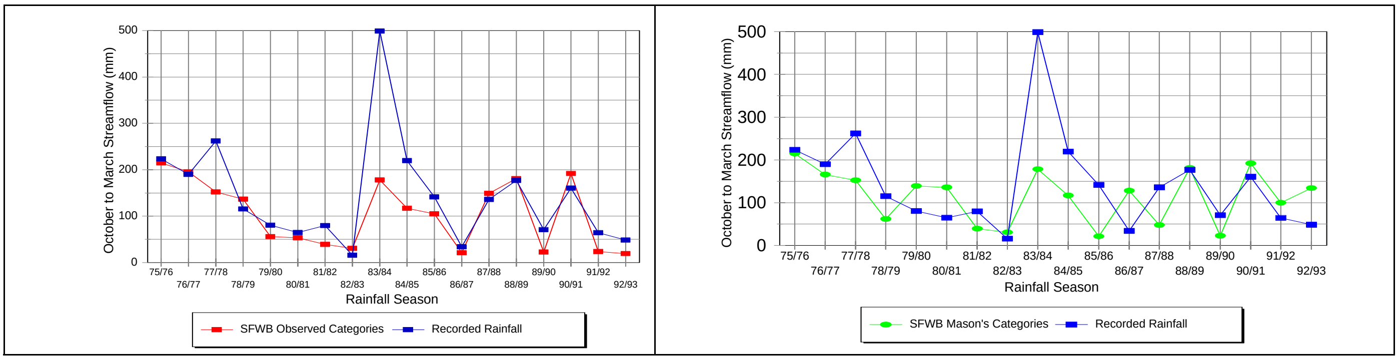

Figure 4. Example of ACRU stream flow output (after Lecler and Schulze, 1997): Seasonal stream flow simulated with recorded rainfall (blue) is compared to stream flow simulated with actual rainfall observations reduced to categorical rainfall (terciles; left) and simulation with categorical seasonal rainfall forecasts (right). The outlier in 1983/84 is due to a tropical cyclone (*Domoina*).

In 1997, the CRG and SAWB agreed, to standardize the output of their improved models and to integrate the results into running three-months forecasts with lead times of up to six months. This was also facilitated by the availability of ensemble seasonal forecasts produced by the Scripps Institute of Oceanography (International Research Institute for Climate Prediction, IRI) and output produced by the United Kingdom Meteorological Office (UKMO) (Mason, 1997). A major milestone before the beginning of the 1997/98 rain season was the creation of the *Southern Africa Regional Climate Outlook Forum* (SARCOF), which initially gathered three times per year representatives from African National Weather Services, affected parties from southern Africa, as well as European and American research organizations, under the leadership of IRI to formulate, disseminate and verify a consensus seasonal rainfall outlook (Held, 1998). An example of such an Outlook is shown in Figure 5. At the end of that year, it was concluded that in view of good progress made with climatological models (Turner, 1997), the main thrust of Eskom's research should now be directed towards the down-scaling of Global Circulation Models (GCMs) in order to achieve further improvements in the forecasting reliability, as well as to encourage meteorologists and hydrologists to embark on direct stream flow predictions (Held, 1997). Subsequently, in the absence of a suitable observational network, a two-tiered forecasting system had been developed, which attempts to provide a forecast of sea-surface temperature conditions over the western tropical Indian Ocean, which, in turn, are used to force a global model to produce ensemble forecasts for southern Africa. The use of this new forecast method has resulted in an improvement in forecast skill, particularly for La Niña (usually above normal rainfall) conditions (Held, 1998; Joubert, 1998).

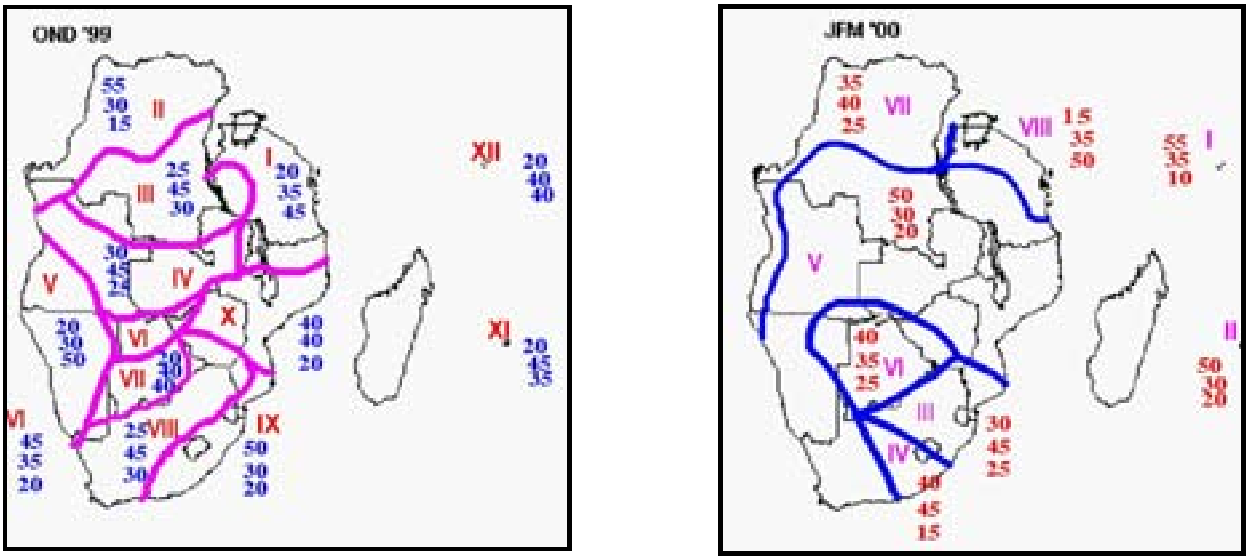

Figure 5. Typical categorical seasonal rainfall outlook (Southern Africa) for the period October to December 1999 (left) and January to March 2000 (right), based on the consensus forecast generated during the September 1999 SARCOF pre-season meeting in Maputo. The maps form part of the written Outlook statement, which details each of the variable forecast regions (depending on predicted rainfall regimes). The forecast is broken down into terciles (above, normal, below) and expressed as a probability (%) of each category.

4. SEASONAL FORECASTING OF STREAMFLOW

Building on the developments and experience gained during past years, Landman *et al.* (1999) of the SAWB continued research into the application of the two-tiered forecasting system and applied it directly to stream flow forecasts, using a statistical approach. Once its feasibility had been established, he deployed various down-scaling methods from dynamic GCMs made available through IRI as a consequence of a two-year Postdoctoral Fellowship at the Lamont-Doherty Earth Observatory of Columbia University, New York (Landman, 2000). This Section summarizes the most recent developments, current state of the art and achievements.

Accepting that rainfall over southern Africa during the main austral rainfall months of December to February (DJF) is affected by sea-surface temperature variability (Mason and Jury, 1997), seasonal stream flow variability may also be related to phenomena such as the El Niño/Southern Oscillation (ENSO) (Schulze, 1997b; Compagnucci and Vargas, 1998). If these phenomena are identified and give a sufficiently strong climate signal in hydrological processes, there is the potential to provide seasonal forecasts of stream flow. Runoff for a given catchment, excluding the effects of dams or interbasin water transfers, is directly affected by precipitation, evaporation and changes in soil water storage (Schulze, 1997b). However, non-climatic factors, such as vegetation cover and the soil surface characteristics of catchments, can play at least an equally important role in determining stream flow (Schulze, 1997b). The rainfall/runoff association is therefore complex, and depends on several factors mostly unrelated to atmospheric variability, which were not directly incorporated into the linear relationships between atmospheric variability and stream flow described in this study.

A multi-tiered forecast scheme for predicting parameters such as naturalized stream flow has been constructed and validated for use in an operational environment. Altogether twelve dams were identified within the Vaal and upper Tugela catchment (green area in Figure 3) that have a sufficiently long training period on which the scheme could be implemented and tested. A retro-active forecast period of eight years from 1987/88 to 1994/95 was used. The method is a multi-tiered scheme involving statistical forecasts of near-global sea-surface temperatures (SSTs), which are used to provide boundary conditions for an atmospheric general circulation model (COLA T30 spectral model of the Center for Ocean-Land-Atmosphere Studies; Kirtman *et al.*, 1997). Simulations of geopotential heights and moisture fields over southern Africa from an ensemble of integrations of the GCM were then used to derive stream flow forecasts using a perfect prognosis technique.

The first step in the procedure involves the SST forecasts. But, before forcing the GCM with the SST forecasts, and then downscaling the simulated fields to stream flow, the potential predictability of stream flow forecasts using this procedure was estimated, by assessing the skill achieved given perfect forecasts of atmospheric variability. A potential for highly skilful forecasts was found for the stream flow of five of the twelve dam catchments. This high potential shows the strong relationship between stream flow and atmospheric variability, and hence suggests that the multi-tiered forecasting system may be able to provide useful skill. Comparing high and low skill scores of stream flow into the various dams, no simple relationship between the strength of a climate signal and its impact on stream flow and catchment size could be found. Larger catchments may have a stronger climate signal because they are less affected by local climate noise, but at the same time the effects of surface characteristics on stream flow may be greater than in smaller catchments. Other non-atmospheric factors, which are probably related to the surface characteristics of a particular catchment, are possibly affecting the variability of certain stream flows significantly.

Using the GCM-derived forecasts of atmospheric fields over southern Africa, and downscaling these to stream flow, accurate forecasts for at least three seasons (1988/89, 1990/91 and 1992/93) during the retro-active eight-year period were achieved, which demonstrates the scheme's potential operational utility, albeit for short lead-times. However, to improve on the confidence of operational stream flow forecasts, a longer training set is required, and more vigorous skill assessments must be conducted. By improving GCM simulations, the potential to make highly skilful stream flow forecasts over relatively short lead-times has been demonstrated to be a possibility, especially if the GCM is supplied with highly skilful SST forecasts that capture the large SST anomalies during strong ENSO events.

Due to their global characteristics, GCMs used in seasonal prediction do not represent details of surface climate well. Their resolution is about 200-300 km, which makes them unable to represent local subgrid-scale features. Therefore, the potential for using a regional climate model at a resolution of 60 km to simulate rainfall and runoff over southern Africa was investigated as an alternative (Landman, 2000). The model used was the NCAR RegCM2, driven with ECMWF analysis data as initial and 6-hourly boundary conditions. Simulations were performed for the DJF seasons when dry (1994/95) and wet (1995/96) conditions, respectively, were observed over a large part of southern Africa.

Deploying the GCM first, it was shown how a statistical downscaling technique, generally referred to as model output statistics (MOS), could successfully be applied to simulate rainfall over a large part of southern Africa, and stream flow at the inlets of some of the dams of the Vaal and upper Tugela river catchments, based on ensemble mean circulation patterns simulated by a GCM forced with observed sea-surface temperatures (Figure 6). High 29-year climate cross-validation correlations were obtained for both rainfall and stream flow, most of which were at least significant at the 95% level of confidence. An anomalously wet DJF rainfall season was observed during 1995/96, and although the MOS forecasts correctly indicated a dry season during 1994/95 and subsequently wetter conditions for the following season (1995/96), they did not capture the large observed anomaly of 1995/96 (about 2 standard deviations above the mean). The ensemble mean GCM rainfall simulated negative rainfall differences (rainfall of 1995/96 – rainfall of 1994/95) over the north-eastern interior of South Africa, which were neither found in the observations, nor in the MOS forecasts (Figure 7). Although the MOS forecasts improved on the GCM prediction of the rainfall differences over the north-eastern region, they are based on semi-empirical relationships between large-scale meteorological fields and rainfall, which have to remain valid under future climate conditions.

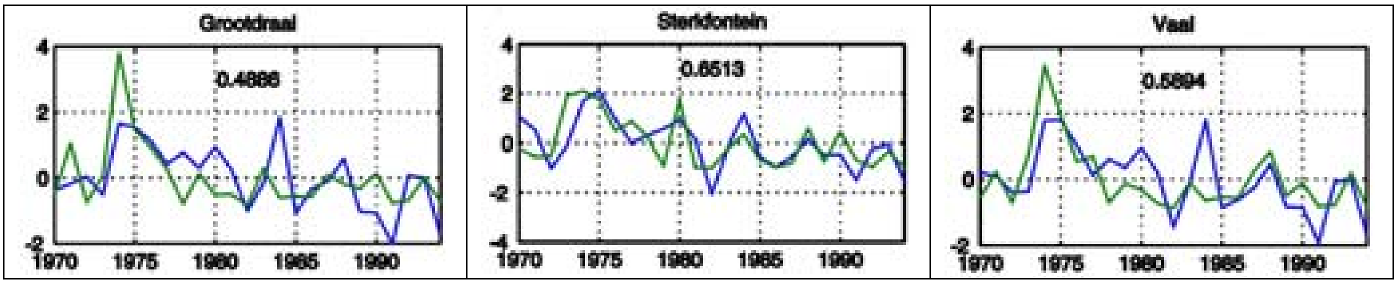

Figure 6. Normalized anomalies of DJF cross-validated MOS stream flow forecasts at the inlets of three dams in the Vaal catchment (Figure 3). Green: observed; Blue: predicted.

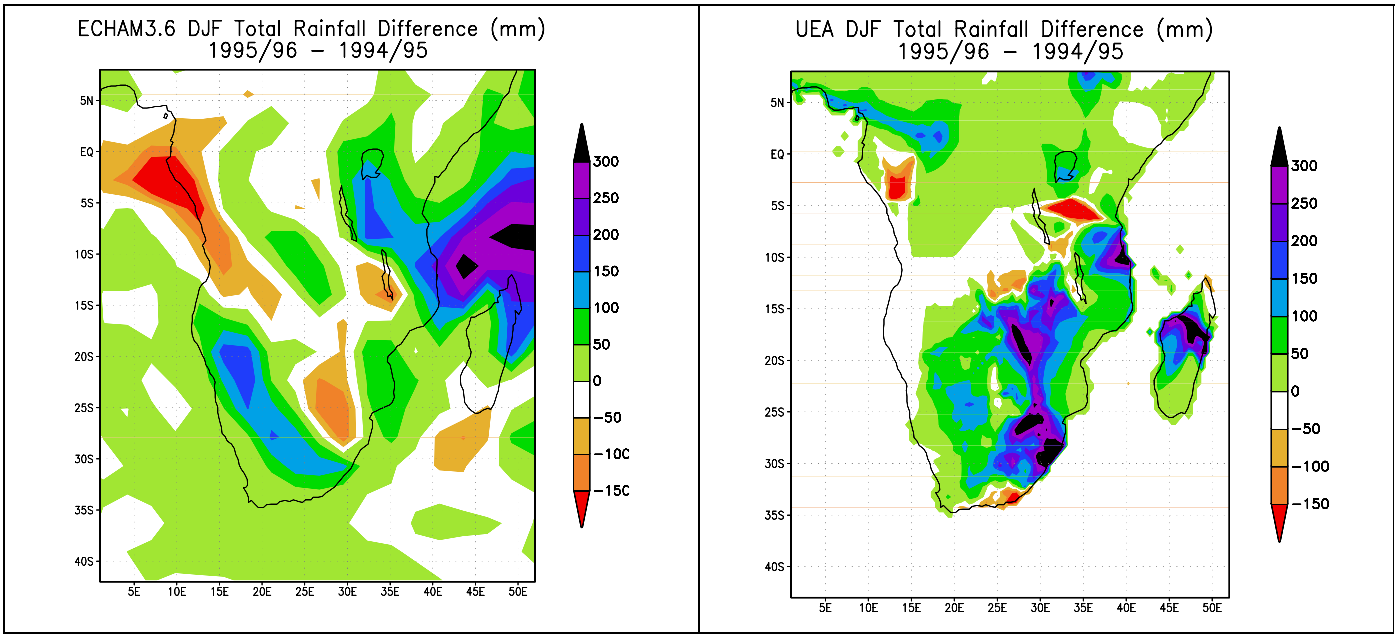

Figure 7. Rainfall differences (mm) between DJF rainfall amounts of 1995/95 and 1994/95. Modeled differences from ECHAM3.6 (left) and observed from UEA data set (right).

Thereafter, the RegCM2 was integrated over the two 90-day periods of DJF 1994/95 and 1995/96, using observed time-dependent large-scale meteorological fields. The model difference rainfall pattern (rainfall of 1995/96 – rainfall of 1994/95) did indicate a wet signal, albeit not as severe as was found in the observed rainfall differences, and also misplaced: the model simulated the largest rainfall differences to be situated over the western, rather than over the eastern interior of central southern Africa. The RegCM2 also favored the southeastern and central interior of South Africa for the occurrence of high rainfall amounts. Although there is an apparent discrepancy between the spatial distribution of simulated and observed rainfall differences, model rainfall differences were found to be mostly positive, which is in agreement with observations. Additionally, mean circulation patterns indicated that the RegCM2 was reasonably successful in simulating lower and mid-tropospheric flow. Investigation into the temporal distribution of simulated rainfall at three major rainfall stations of the summer rainfall region suggested that the RegCM2 is yet unable to adequately capture the temporal distribution of particular grid-point rainfall. However, it was more skilful in simulating the frequency of a range of rainfall thresholds. Whatever success and failures the RegCM2 would have in simulating rainfall amounts and distribution, the same would most likely be applicable to simulating runoff, notwithstanding the fact that simulated rainfall amounts outweigh simulated runoff amounts by a factor of five or six, a high temporal correlation was found when the area-average simulated rainfall amounts over a region overlaying the Vaal and upper Tugela catchments were compared with area-averaged observed runoff amounts of the same region (Figure 8).

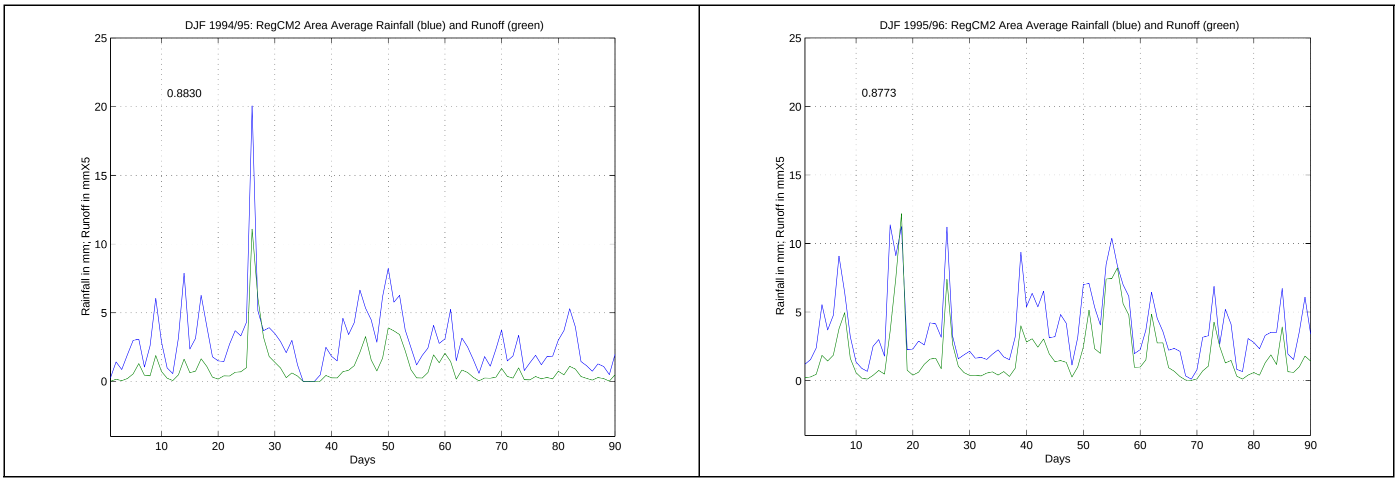

Figure 8. Simulated area-averaged rainfall (mm, blue) and runoff (mmX5, green) of DJF 1994/95 (left) and 1995/96 (right). The correlation between the rainfall and runoff is shown in the top left corner of the graph.

Landman (2000) concluded that further research into the seasonal variability and predictability related to spatial scale through the use of regional models is necessary. Firstly, more runs of the main rainfall season of DJF, when the RegCM2 is driven by observed meteorological fields, need to be conducted in order to get a better understanding of the model's systematic errors, and also to get a better expectation on its ability to simulate features such as tropical cyclones that could dramatically affect the seasonal rainfall variability over southern Africa. Ultimately, in order to use the RegCM2 operationally over an extended lead-time, it has to be nested into GCM-simulated large-scale meteorological fields, preferably for a number of ensemble members.

5. A RAINFALL-RUNOFF MODEL DRIVEN BY SEASONAL RAINFALL FORECASTS

The objective of the hydrological sub-project was the development of a model that is able to generate stream flow, both past and forecasted, from monthly rainfall records. Due to the complexity of predicting runoff, average monthly rainfall alone cannot be used, because it fails to take into account the short periods of infiltration before and after storm events as well as ground water contributions. Many rainfall to stream flow models exist, with the Stanford watershed model (Crawford and Linsley, 1966) and the Pitman model (Pitman, 1973) being two well known models. These models, however, are empirical and not based on hydrodynamic principles. Periods of intense rainfall produce non linear rainfall-runoff relationships, while groundwater flow becomes more prevalent in runoff during drought periods. Empirical or semi-empirical models fail to take this into account and these conditions produce shortcomings.

The *Rafler* model, which was used in this pilot study (Stephenson and Paling, 1992), is a conceptual deterministic model, which uses past rainfall to determine antecedent soil moisture conditions, and forecasted monthly rainfall, to predict monthly stream flow. It is based on the simplified hydrodynamic equations for overland flow and the simplified Green Ampt infiltration model for vertical flow into the soil and underlying aquifers. It uses monthly rainfall data and basic catchment parameters to estimate runoff. All parameters, except two calibration parameters, are physical characteristics that can be measured or obtained from literature. Some aquifer characteristics which are hard to measure can be obtained by calibration. Overland flow takes into account factors such as slope, roughness, width and length of flow. Since overland flow is not in sheets a factor, the rill ratio is introduced to take into account the rivulet nature overland flow. Infiltration is assumed to be plug flow and the infiltration rate is required. The emergence of groundwater flow or interflow between aquifer layers can be included. The model operates on an hourly time interval, although the input and output are in monthly intervals, which makes it less sensitive to observational errors in daily rainfall records. The rainfall intensity during a particular month is found from the ratio of monthly rain and the number of rain hours per month. Rather than spreading the rain over the entire month, it is assumed that precipitation occurs uninterrupted at the beginning of each month.

In order to test the suitability and accuracy of the *Rafler* model, it was first deployed to calculate river flows in the Caledon river (Figure 3), a small 13 400 km^2 catchment, using 10 years of monthly flows. Measured flows were reproduced reasonably well, and it is therefore expected to also predict future river flows (Stephenson *et al.*, 2000; an example will be shown in the presentation). However, the biggest discrepancies were found for the peak run-off.

Subsequently, the model was expanded to estimate flows at different positions along the Orange river (Stephenson and Randell, 2000). The Orange river catchment is the largest in South Africa, comprising 48% of the country's total area, but contributes only 22% to the total mean annual runoff. In Figure 3 only part of its catchment is shown, viz. approximately 89700km^2 upstream of the Vanderkloof dam, which was used for the model validation. The Orange river and its tributaries supply water to many towns and numerous large-scale irrigation projects, since the region is relatively arid, receiving less than 550mm/annum and is heavily dependent on the water. The simulated flows were compared to measured flows from various stations, which were measured prior to the construction of any of the larger dams and the catchment was modeled accordingly. Reservoirs were then included to display the operation of the dams.

The model, now called RAIROFF (Stephenson and Randell, 2000), was also modified to accept categorical seasonal forecasts as input in the form of monthly probabilities of expected rainfall. The model user interprets these forecasts and inputs the forecasted data either as rainfall data appended to the existing rainfall data files or as percentiles of the mean monthly expected rainfall, where 100% represents the mean monthly values. The model calculates mean monthly rainfall for each rainfall station, from the input data. These values are assumed to represent the 100% expected monthly rainfall. When predicted rainfall is added to the model in the form of percentiles of mean monthly rainfall, the model uses these predicted percentiles to calculate the forecasted monthly rainfall and calculates the expected flows. The deterministic model does not differentiate between the actual and predicted rainfall data as it does the same calculations whether the rain is actual or predicted.

The model provided adequate simulated stream flow data which compared favorably with measured flows and proved that it was capable of operating the reservoirs. The time horizon for which the model is reliable depends on the accuracy of the weather prediction and this will improve with time. However accurate the predicted flows are, they are likely to be of greater value than the use of average or probable flows each month. Prediction of lower or higher flows than normal will enable reservoirs to hold back or release water accordingly and so optimize the power output. The accuracy of the calculated mean monthly rainfall will be dependent on the length of the rainfall data set that is entered into the model. A maximum of 50 year's historic data is allowed to achieve the best results in terms of memory allocation and execution time.

6. CONCLUSIONS

Already in 1993, the South African electricity utility, Eskom, had anticipated the need for strategic planning and managing of water resources required for cooling of its large thermal power stations, especially in view of the country still recovering from one of the major El Niño events in 1991/92, which resulted in extensive droughts on the South African plateau. Due to the seasonality of rainfall on the plateau, very few rivers are perennial and thus suitable for hydroelectric power generation. This explains the fact, that only 5% of Eskom's installed generating capacity is in form of hydroelectric plants, of which only two are base load stations on the Orange River, with the other two being storage-pumping-plants for peak power generation. However, since the agricultural sector also requires large amounts of water for irrigation purposes, it is equally important to strategically plan the annual operation of the hydro power stations, especially ahead of anticipated drought periods.

This review has clearly demonstrated, that statistical climate prediction models are suitable to indicate expected rainfall safely up to three months, with a further three month of anticipated conditions, especially when combined with downscaled results from Global Circulation Models (GCMs). Furthermore, it was shown, that such a scheme can also be designed to predict stream flow directly. On the other hand, it is not so much the predicted rainfall totals, which are of importance for strategic planning purposes, but the amount of water, which ultimately ends up in the storage dams. Therefore, hydrological models were reconfigured and tested to accept categorical rainfall predictions instead of daily rainfall to produce three-monthly stream flow data and dam volumes. This would enable reservoir releases to be optimized in advance, as the expected inflow is known with greater certainty, which would then result in more hydro power (± 10% = 1 MW), as water does not have to be stored for uncertainty. Based on current costs and operating procedures, the value of the additional power could amount to about ZAR 1 mill/year (± US $ 100 000). Although preliminary results from stream flow models are encouraging, further fine-tuning and verification will have to be done before the results become credible in the eyes of hydrologists and decision makers.

A survey on the benefits of incorporating seasonal forecasts into operational planning of water management, industrial applications (e.g., electricity sector) and agricultural activities was conducted amongst the user community during the 1998 SARCOF meeting. Harrison and Graham (2001) concluded, that the average annual value of seasonal forecasts in Southern Africa is in the order of US\$ 10^8 to \$ 10^9. Based on marginal costs of providing climate information by the regional National Meteorological Services (NMS), they estimate the benefit/cost ratio to be between 20 and 200, indicating potentially huge savings if seasonal forecasts are interpreted correctly and consequential decisions for planning activities taken.

From what had been elaborated above, it is obvious, that continued support of research into downscaling of GCMs to stream flow and the implementation of hydrological models using seasonal forecast information as rainfall input is absolutely essential and a valuable investment into the future of any electricity utility. However, the best prediction becomes useless, if good rains fall during the wet season in a particular region, but the storage volume of the dams is insufficient.

In view of the severe drought having affected the majority of States in Brazil during 2001, which resulted in drastic cuts of allocated electricity to all consumers for a prolonged period, the following lessons from the above review should be noted -

- The Centro de Previsão do Tempo e Estudos Climáticos (CPTEC) and Instituto Nacional de Meteorologia (INMET) already provide categorical seasonal consensus forecasts on a monthly basis. However, the electricity generating sector should join with these organizations and invest into further research of the downscaling and prediction models for seasonal forecasts, as well as the fine-tuning for local conditions in Brazil and verification of outputs. Using the South African model, the most economical way to achieve this would be through the involvement of suitably qualified Universities (giving grants for MSc and PhD students), which could subsequently develop into "Centers of Excellence".
- Education of possible users and affected parties, but especially the media, in interpretation, confidence limits and application of categorical seasonal forecasts is of utmost importance, best achieved through small Workshops and widely distributed explanatory notes.
- Strategically located S-band radars should be utilized to monitor areal rainfall in space and time for the accurate determination of the antecedent conditions of the catchments, as required by hydrological models, and the validation of the forecasts. Currently, satellites and telemetered rain gauge data can only partially fulfill this task, but should be used to supplement radar observations.
- Furthermore, the operational companies must ensure, that there is sufficient storage volume available to capture most rainfall during wet years, for release during the drier periods, which will alleviate the need for drastic reductions in electricity consumption due to water shortage. This obviously not only entails the construction of new storage facilities, but also good maintenance of existing dams in terms of clearing accumulated silt and preventing future silting.

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